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# THE SEQUENTIAL SPARK TECHNIQUE: A TOOL FOR WAKE VELOCITY STUDIES IN BALLISTIC RANGES

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by

C. Lahaye and others

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## RÉSUMÉ

Depuis quelque six ans, le Centre de recherches pour la défense, Valcartier (CRDV) poursuit dans ses corridors balistiques un programme d'étude des sillages produits par des projectiles hypersoniques. La technique des étincelles consécutives est l'une des méthodes qui ont été développées au cours de ce programme pour mesurer la vitesse du sillage. Elle est fondée sur la formation, dans le sillage, d'un chemin ionisé et lumineux par une première étincelle et sur la réillumination périodique de ce chemin par des étincelles consécutives. Comme le sillage entraîne avec lui le chemin ionisé, chaque étincelle apparaît déplacée proportionnellement à la vitesse du sillage. Par photographie, on obtient un profil du déplacement du sillage à partir duquel on peut calculer la vitesse. Depuis 1966, cette technique a fourni de nombreuses données nouvelles sur la distribution de la vitesse dans le sillage de maquettes sphériques et coniques. Ce rapport explique la technique des étincelles consécutives, y compris l'appareillage spécialement conçu pour produire ces étincelles. Une nouvelle technique servant à choisir la position de l'étincelle et à la déplacer dans un arrangement d'électrodes est décrite. Cette technique utilisée dans le sillage des sphères a permis de mesurer des profils de vitesse multiples durant le même tir. Lors des mesures faites dans le sillage des cônes, elle a permis de produire l'étincelle à une position prédéterminée par une série de détecteurs servant à localiser la ligne de vol du projectile dans le corridor de tir. Les méthodes d'enregistrement et de réduction des données sont décrites. La précision et la résolution de la technique sont étudiées et, finalement, quelques résultats typiques sont présentés.

## ABSTRACT

For more than six years, the Defence Research Establishment Valcartier (DREV) has been carrying out a program of investigation of turbulent wakes in its ballistic range facilities. One of the experimental techniques used in this program has been the sequential spark technique which makes use of electrical discharges (sparks) in sequence to measure velocity profiles in the wake of projectiles in free flight. This experimental technique is based on the formation of an ionized luminous path in the wake by a first spark and on the periodic re-illumination of the displaced ionized path by successive sparks. Open-shutter photography yields a profile of the displacement of the path which can be used to calculate the velocity. This unique technique has produced, since 1966, a wealth of velocity data on the wakes of hypersonic spherical and conical models in free flight. This report presents a comprehensive review of the sequential spark technique. A description is given of the equipment which has been designed to produce the sparks. A new technique developed to select and switch the position of the spark in an array of electrodes is also explained. This technique as applied to sphere wake measurements has permitted the production of multiple velocity profiles in the wake of the same projectile. Applied to cone wake measurements, the technique has been used to switch the spark to a position predetermined by a series of detectors used to locate the flight line of the projectile in the range. The recording and data reduction method is described. Accuracy and resolution of the technique are discussed. Finally typical results are given and environmental conditions under which the sequential spark technique is applicable are outlined.

## TABLE OF CONTENTS

# 1.0 INTRODUCTION

Over the past decade, the turbulent wake produced by hypersonic projectiles re-entering the atmosphere has been the subject of considerable theoretical and experimental research effort. Theoretical studies directed at determining a workable model of the turbulent wake revealed the need for spatially resolved measurements of the physical properties of the wake to support the development of the different models and their evaluation. Since the measurements in the wake of actual re-entry vehicles were impractical, ballistic range facilities have been used to produce wakes extending over thousands of projectile diameters under simulated upper atmosphere conditions.

Since 1965, the Defence Research Establishment Valcartier (DREV) has been carrying out a wide-ranging program of experimental investigation of turbulent wakes in its ballistic range facilities. A number of experimental techniques have been developed and used to make spatially resolved measurements of the mean distribution of such quantities as temperature, velocity and mass and electron densities in the wake of hypersonic projectiles (1, 2). One of the experimental techniques used in this program is the sequential spark technique, which makes use of electrical discharges (sparks) in sequence to measure velocity profiles in the wake of projectiles in free flight. Since 1966, this experimental technique has produced a wealth of velocity data behind spherical and conical models (3, 4).

This report presents a comprehensive review of the sequential spark technique. A description is given of the equipment which has been designed to produce the sparks. A new technique developed to select and switch the position of the spark in an array of electrodes is also explained. This technique as applied to sphere wake measurements has permitted the production of multiple velocity profiles in the wake of the same projectile. Applied to cone wake measurements, the technique has been used to switch the spark to a position predetermined by a series of detectors used to locate the flight line of the projectile in the range. A description of the recording and data reduction method is given. Accuracy and data resolution of the technique are discussed. Finally, typical results are given and environmental conditions under which the sequential spark technique is applicable are outlined.

# 2.0 THE SEQUENTIAL SPARK TECHNIQUE

## 2.1 Principle of the Technique

The use of sparks for the measurement of the velocity distribution in flowfields is founded on the following three properties of the spark: the ionization of a narrow filament of gas, the strong emission of light from that filament and the persistence of appreciable ionization for some time after the spark. When a spark is made across a flowfield (for example, the wake of projectile) the ionized filament formed by this spark is displaced at the velocity of the neutrals.

Successive sparks made at selected intervals retrace the displaced path of the first spark due to the persistence of the ionization. The light emitted by the sparks can be used to make a photographic record of the successive positions of the ionized path. This record of the displacement can be used in conjunction with the time interval between the sparks to calculate the velocity distribution of the flowfield.

The display of Figure 1 shows the stereo photographs of a typical sequence of sparks made at a distance of 600 body diameters behind a one inch diameter aluminum sphere travelling at 14,500 ft/sec in the range at an ambient pressure of 40 torr. In this case, a sequence of seven pulses at intervals of 40 microseconds has been used. The schlieren photograph in the center of the arrangement shows the flowflied at the time of the measurement with the spark technique. The boomerang-shaped electrodes seen in the photographs represent an early attempt to obtain straight sparks.

Bomelburg, Herzog and Weske (5, 6) were the first to use sparks in sequence to measure flowfield velocity. They used the technique to measure gas velocities in a variety of situations from the subsonic flow in pipes to the laminar boundary layers of transonic and supersonic flows in wind tunnels. In these latter experiments, the model under test was used as one electrode, the other electrode being a metal ring in the wall of the wind tunnel. Kyser (7, 8) also used the spark technique to study hypervelocity flowfields in a wind tunnel at pressures of one to ten torr. He developed a technique for reducing the spark width at these low pressures. Finally, Frungel (9) gives a good description of the spark technique and discusses some of its applications.

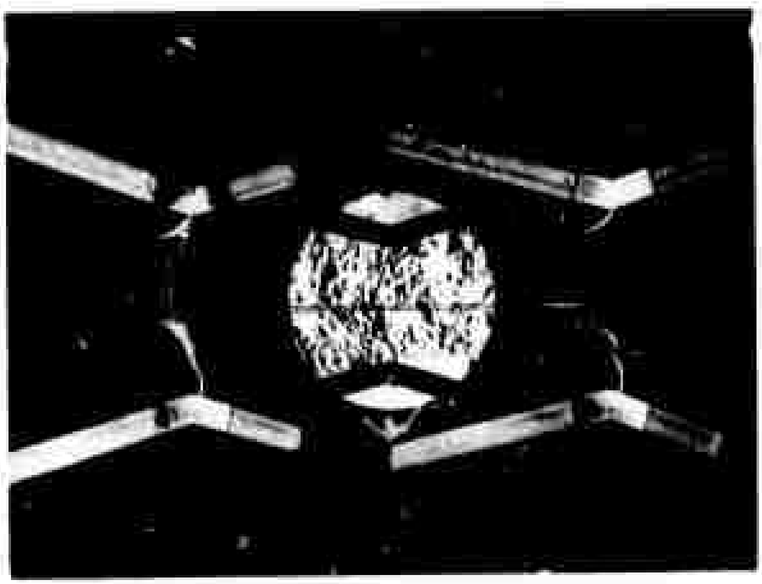

**FIGURE 1 – Typical Sequence of Sparks Made at 600 Diameters Behind a Hypersonic Sphere. Schlieren Photograph Shows the Wake at the Time of the Sequence.**

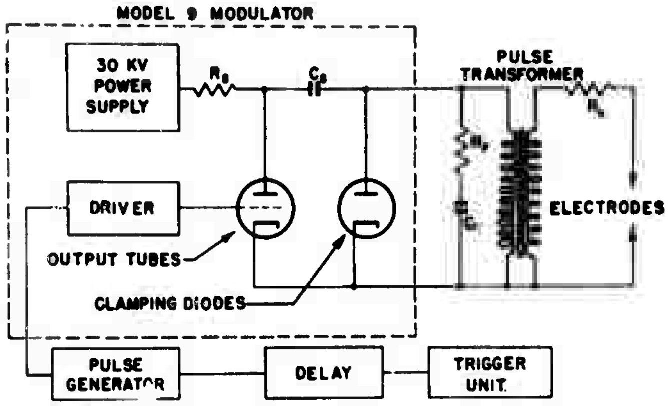


**FIGURE 2 – Diagram of the Sequential Spark Apparatus**

## 2.2 Production of the Sparks

The application of the sequential spark technique to the measurement of the velocity in the wake of free-flight projectiles in a ballistic range necessitated the use of fairly large electrode gaps compared with the wind tunnel application mentioned above. Gaps of 5 to 7 inches were required to allow for the dispersion of the projectiles and to provide a reasonable coverage of the wake of one inch diameter spheres. These large gaps, in turn, necessitated the use of very high voltage short duration pulses to achieve rapid breakdown of the gap. Current-wise, the intensity of the spark had to be sufficient for photography. Time-wise, the possibility of repeating the pulses at a minimum interval of a few microseconds was required. This requirement of a fast repetition rate precluded the use of a high voltage thyratron in conjunction with a pulse forming network, a technique often used in radar technology to turn on the magnetron at a low repetition rate. For high repetition rates, so-called "hard tube modulators" are used. The equipment which produces the sparks has been developed from one of these modulators, the MIT Model 9, which has been described in the literature (10).

Figure 2 shows a block diagram of the equipment used to generate the high voltage pulses required to produce the sparks. The Model 9 hard tube modulator is shown schematically inside the dotted line area. It operates in the following way: the 30 Kv power supply charges a large energy storage capacitor up to 30 Kv through the series resistor $R_S$ and through the primary of the pulse transformer. The plates of the output tubes are then at high voltage. The grids of the output tubes are biased to cut-off by a high negative voltage. When a positive pulse is applied to the grids, the output tubes are switched from cut-off to full conduction. The voltage across the output tubes decreases to a few kilovolts, and a high negative voltage is applied to the primary of the pulse transformer. A high positive voltage is induced in the secondary and applied to the electrodes. The output tubes remain in this conducting state until the driving pulse on the grids is removed. Clamping diodes are used to prevent high frequency oscillations when the output tubes are switched to cut-off.

Experimentation indicated that the 30 Kv pulses furnished by the modulator were insufficient to obtain rapid breakdown across a 6 inch gap and that voltage pulses of the order of 90 Kv would be required. A 3 to 1 pulse transformer was made to order by Pearson Electronics Inc. to increase the output voltage to 90 Kv. The large currents required to charge the stray capacitance within the pulse transformer and to magnetize the core made it necessary to modify the Model 9 modulator. A lack of current resulted in a deterioration of the output pulse rise time. Consequently, the power output of the modulator was doubled by increasing from 3 to 6 the number of 6C21 output tubes and by increasing accordingly each stage of power amplification of the driver unit. With this modification, three megawatt pulses were fed to the primary of the pulse transformer. This was sufficient to assure a rapid rise time of the voltage on the secondary. With the equipment described above, 0.8 microsecond pulses at 90 Kv were available at the electrodes with a maximum current of 20 amperes in the discharge.

A few more modifications were made to the modulator. The capacitance of the energy storage capacitor $C_s$ was increased from 0.125 to 0.5 microfarad in order to reduce the loss of voltage when many voltage pulses were needed as, for example, in the case of multiple sequences that will be discussed later. Modifications were also made in the multivibrator-delay line part of the driver unit to reduce the reset time of the equipment to three microseconds.

Special care had to be taken to feed the high voltage pulse from the secondary of the 3 to 1 step-up transformer to the electrodes inside the range. Stray capacitance of the elements in the secondary circuit is much more detrimental to the pulse rise time than the capacitance of the primary circuit. To reduce this capacitance, the pulse transformer was mounted on top of the range in close proximity to the electrodes and the secondary of the transformer was connected to the electrode inside the range through a three inch diameter nylon bushing containing a string of 2 watt resistors ($R_1$) totaling 1,000 ohms. This string of resistors is used to prevent short-circuiting of the secondary of the transformer once the discharge is initiated across the electrodes. Attempts to reduce the spark width at the lower pressures by increasing the resistance to limit the current in the sparks had very little success. A series combination of the resistance $R_f$ and of the capacitance $C_f$ in parallel with the primary of the transformer is needed to eliminate unwanted oscillations and to obtain a square voltage pulse on the secondary of the transformer.

## 2.3 Control Equipment

In contrast to most wake experiments, which collect information on a continuous basis over the full length of the wake, the sequential spark experiment has to be operated in a triggered mode; the sequence of sparks is made across the wake at selected intervals depending on the gas flow velocity and at a selected distance (time) behind the projectile. This triggered mode operation is represented in the block diagram of Figure 2. The control equipment consists of a

"trigger unit" from which the knowledge of the axial position of the projectile in the range is acquired, a delay unit which allows the projectile to travel a selected distance, and a pulse generator which produces the desired number of voltage pulses at selected intervals and feeds them to the modulator.

Knowledge of the axial position is obtained from the velocity measurement and photoattitude systems of the range. The passage of the projectile at a station is detected by a combined light-screen-photo-electric device and photo-multiplier tube unit which detects either the interruption of the light beam by the projectile or the light emitted by the projectile. A triggering pulse from this unit starts the stereo flash X-ray photoattitude station which provides a photographic record of the position of the projectile and also starts the delay controlling the pulse generator. The adjustment of the delay presupposes a good knowledge of the projectile velocity since the distance travelled by the projectile during the delay depends on its velocity.

To generate the sequence of pulses necessary to perform the wake velocity measurement, special pulse generators have been designed. An early version using discrete semi-conductor components consisted of asymmetric multivibrators giving 0.8 microsecond pulses at time intervals adjustable between 3 and 200 microseconds. An adjustable gate controlled the number of pulses fed to the modulator. A latter version made with micro-logic components used a one megacycle clock. Standard techniques were used in the design of these two different types of pulse generators. For this reason these circuit diagrams are not given here.

The selection of the interval required between the sparks for a given measurement also presupposes a rough knowledge of the velocity of the flow. The maximum displacement between consecutive sparks is usually limited to 10 to 20 percent of the flowfield width to avoid large curvatures of the spark path which may be detrimental to the accuracy of the measurement. A typical sequence of pulses for velocity measurement in the wake consists of a train of four pulses at intervals of three microseconds to form the ionized path followed by a series of 2 or 3 pulses at intervals determined from the above mentioned rule of thumb. The use of the rapid train of four pulses circumverts the problem encountered in the sequence of Figure 1 where only the third pulse of the sequence formed a reasonably defined spark. Experimentally, it was determined that the persistence of the ionized path was sufficient to allow measurements with spark intervals as high as 200 microseconds.

## 3.0 SELECTION OF THE SPARK POSITION IN AN ELECTRODE ARRAY

The need for a technique to permit the selection of the spark position in an array of electrodes became apparent when velocity measurements were attempted in the wake of conical projectiles. It appeared that the probability of getting the sparks through the viscous wake of a cone was very low because of the small diameter of the wake and the large dispersion of the shot on cone firings. These facts suggested the use of an array of detectors to determine the position of the

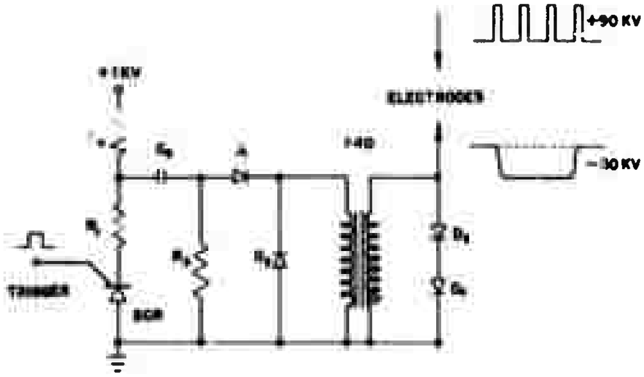


**FIGURE 3 – Simplified Circuit Diagram of the -30 Kv Pulse Generator**

cone close to the spark station in the range and the possibility of switching the spark position accordingly in the corresponding array of electrodes.

Several techniques were known to reduce the breakdown voltage across electrodes gaps: irradiation of the gap with a mercury-arc lamp, with radioactive materials or with ultraviolet light; the use of an auxiliary spark gap on one of the electrodes, the use of radio frequency signals (12). These techniques were generally used with small gaps and were found either ineffective or impractical on large gaps. One further constraint in the case of the sequential spark equipment was that no circuitry could be connected to the high voltage electrode because of the possible deterioration of the rise time of the voltage pulse.

A new technique was developed to permit the selection of the spark position in electrode arrays. The selection is effected by creating a distortion in the electric field across the gap of the chosen electrode pair. This distortion of the field is produced by the application of a -30 Kv pulse on the cathode at the same time as the +90 Kv pulses are applied on the anodes, giving a potential difference of 120 Kv across the selected electrode gap compared with 90 Kv across the other gaps.

Figure 3 shows a simplified circuit diagram of the pulser which was designed to generate the -30 Kv pulses. The capacitor $C_s$ is charged to 1 Kv through the resistor $R_2$ and the primary of the transformer. When a triggering pulse is applied to the gate of the silicon controlled rectifier (SCR), it becomes conducting and the capacitor $C_s$ is discharged in the primary of the pulse transformer. A high negative pulse is induced in the secondary of the 40 to 1 step-up transformer and applied to the bottom electrode to perform the selection of the spark position. The amplitude of this pulse is limited to -30 Kv by the two 15 Kv diodes in parallel with the secondary. The purpose of these diodes is to by-pass the secondary during the sparks, otherwise the spark current would damage the pulse transformer. The pulse width of 10 microseconds is determined by the time constant $R_1$ $C_s$. The

resistor $R_1$ limits the current through the SCR. The diodes D1 and D2 are used to block the negative voltage pulses generated by the spark and reflected in the transformer, while the positive swings are blocked by D3 and D4.

The selection of the spark position depends heavily on the accurate synchronization of the voltage pulses applied to the anode and cathode. To assure proper operation, the -30 Kv pulse must be near its maximum value (Figure 3) when the first +90 Kv pulse is applied to the anode. This first pulse of the sequence produces a glow across the gap and the success of the selection depends on the concentration of the glow current on the selected electrode pair. As will be seen later, there is a limit to the amount of precession that can be given to the -30 Kv pulse because of the possibility of voltage breakdown between adjacent cathodes.

## 3.1 Multiple Spark Sequences on Spheres

The first application of the technique for selecting the spark position was in the production of multiple spark sequences on the same sphere firing. This feature of the sequential spark technique has facilitated considerably the collection of statistically meaningful amounts of data required for the determination of the mean characteristics of the turbulent wake of hypersonic spheres.

To obtain multiple sequences of sparks on the same firing, pairs of point electrodes are disposed axially along the flight axis with a separation of three to four inches. Figure 4 shows a block diagram of the instrumentation used to produce multiple spark sequence measurements. The +90 Kv pulse sequences are applied to the anodes

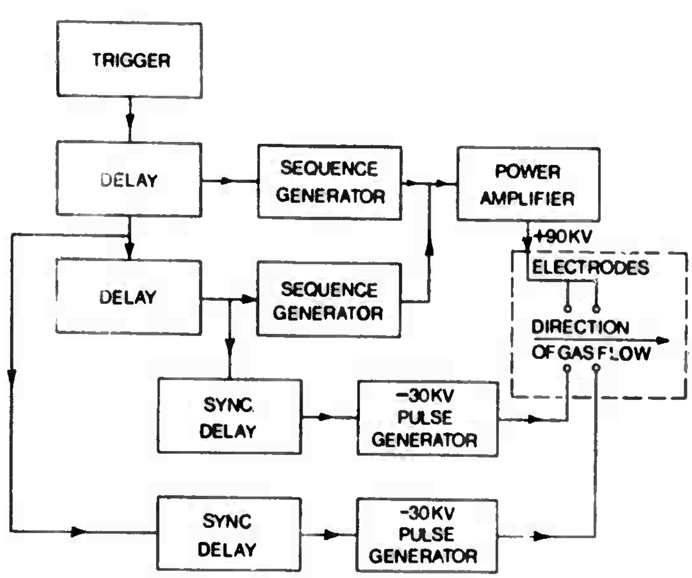


**FIGURE 4 – Diagram of Instrumentation Used for Multiple Sequence Production**

connected in parallel. A -30 Kv pulse generator is connected to each of the cathodes to perform the switching of the spark position on each sequence. As described previously, a triggering pulse is obtained from a flash X-ray photoattitude station. This pulse is fed to a delay adjusted to obtain a measurement at the desired axial distance in the wake. The output of the delay is fed to the pulse sequence generator and to a -30 Kv pulse generator through a synchronizing delay. The output of the first delay is also fed to a second delay which determines the time of the second spark sequence. The output of this second delay is used to trigger a second pulse sequence generator and a second -30 Kv pulse generator.

A few conditions must be observed to obtain proper switching of the spark sequences. The first sequence of sparks has to be made on the downstream set of electrodes to make use of the fact that between the first sequence and the second, the gas flow is convected away from the electrodes and replaced by a new upstream portion of the wake. The second sequence is made on this new portion. Experiments in still air with this set-up have shown that no switching occurred even with delay of 15 milliseconds between the two sequences. Thus the switching

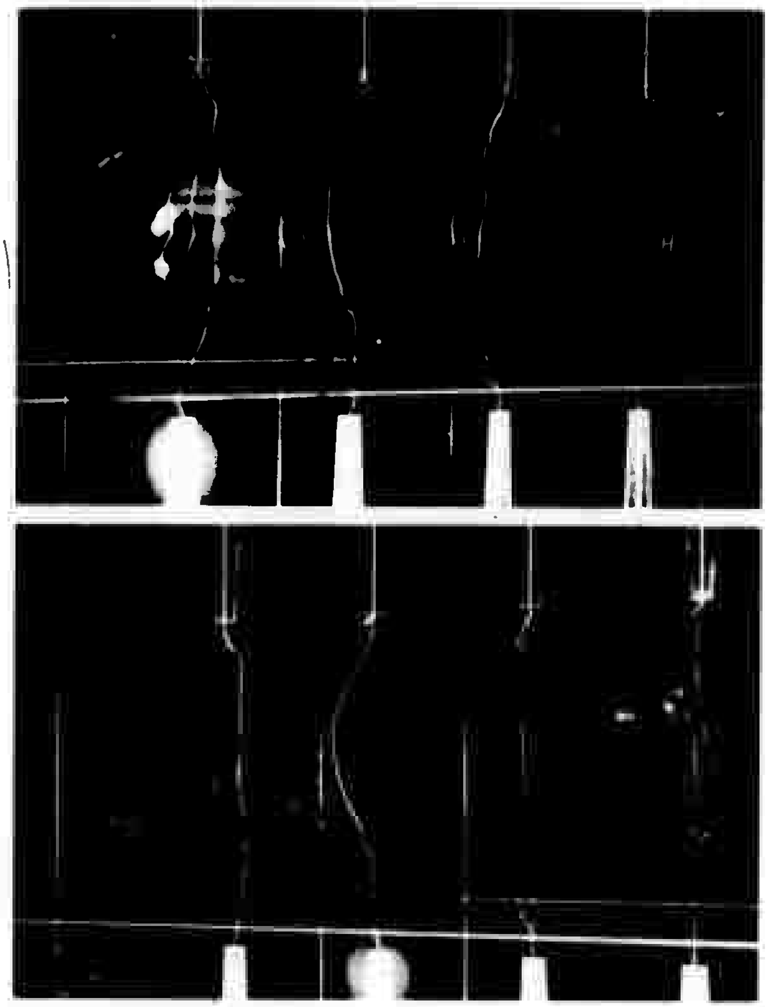

**FIGURE 5 – Stereo photographs of Four Sequences of Sparks Made in the Wake of a Hypersonic Sphere**

depends heavily on the removal of the column of gases heated by the sparks and probably still slightly ionized. The switching becomes marginal when the width of the moving core is small with respect to the electrode gap. It is obvious that switching to the second set of electrodes also depends strongly on the synchronization of the -30 Kv and +90 Kv pulses. In practice, switching has been made with intervals as short as 0.75 millisecond between sequences.

Figure 5 shows the stereo photographs of four sequences of sparks made in the wake of a one inch diameter aluminum sphere travelling at 14,500 ft/sec at an ambient pressure of 100 torr. These four sequences (from left to right) in each of the stereo photographs were made at axial distances of 500, 900, 1,500 and 2,750 body diameters with spark intervals of 35, 75, 120 and 175 microseconds respectively. The electrodes are made of 1/32 inch steel rods insulated by two 1/32 inch thick sheets of plexiglas glued together to cause minimal interference with the flow. The steel rods of the cathode were recessed by one inch inside the plexiglas insulator to prevent breakdown of the gap between adjacent cathodes by the -30 Kv pulses. In the present case, the number of possible sequences is limited by the field of view of the stereo cameras.

### 3.2 Measurements on Cones

The small diameter of the wake and the large dispersion of the gun on cone firings dictated the use of detectors to determine the position of the cone at the spark station and the possibility of selecting the position of the sparks in a corresponding array of electrodes. To accomodate the small size of the cones (one inch base diameter or less), the detectors and, consequently, the electrodes had to be separated by a comparable distance. This requirement precluded the use of a transverse array of electrodes similar to the axial array used on spheres; the closeness of the anodes would have made necessary the use of a technique to make the selection of the spark position on the +90 Kv anodes with a consequent degradation of the risetime of the pulse.

Figure 6 reproduces a photograph taken outside of the range of the detector-electrode assembly used for the measurement of wake velocity on cones. The electrodes seen on the left consist of a transverse array of eight cathodes located on a 60° arc of circle of 5½ inch in radius with a single anode located at the center of the circle. The eight detectors and the light source (a filament lamp) seen on the right are disposed in the same geometry as the electrodes and are located about two feet ahead of the electrodes. With this geometry, the detector-electrode assembly covers a transverse area defined by an equilateral triangle of 5½ inches in side. This coverage in the transverse plane of the range was sufficient to increase the probability of success to about 75 percent.

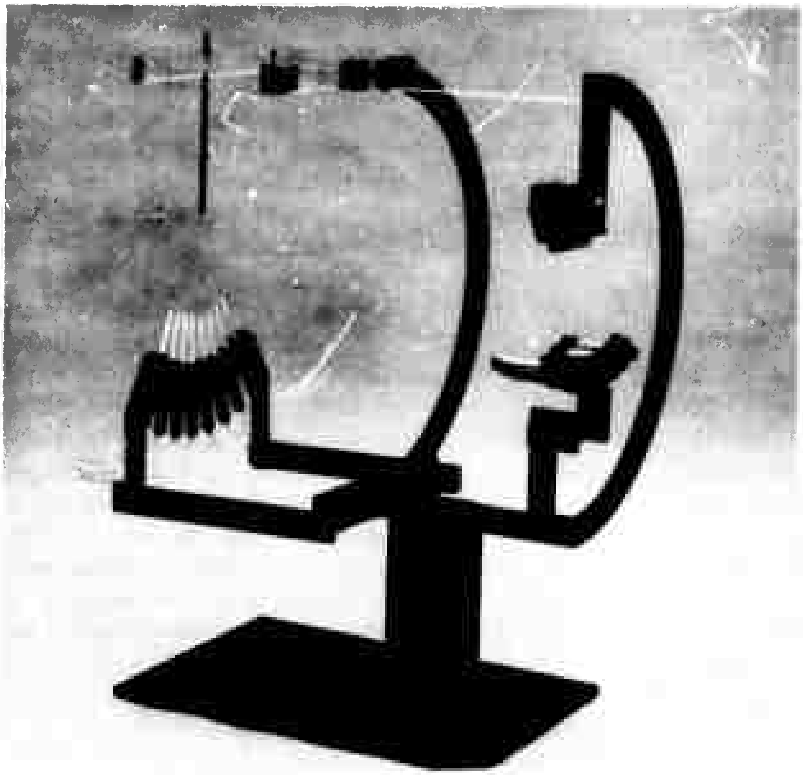

FIGURE 6 – Detector-electrode Assembly Used on Cone Wake Measurements

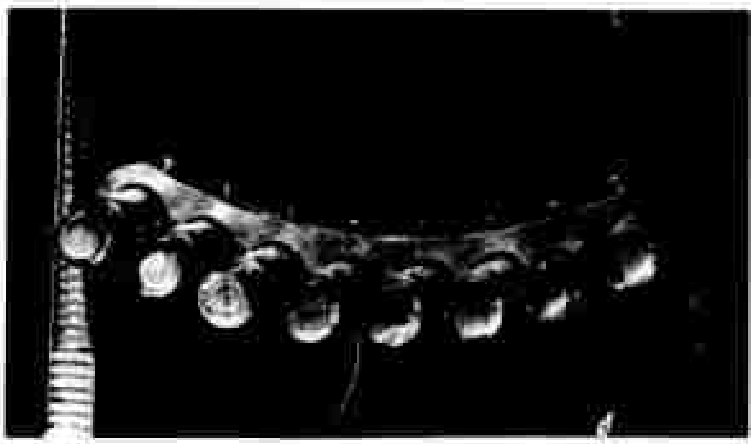

FIGURE 7 – Close-up of the Detectors

Figure 7 shows a close-up of the detector assembly photographed inside the range. Each detector consists of a 927 photocell followed by a field effect transistor input stage and a bipolar transistor output stage providing current gain. Bootstrapping techniques are used to increase the input impedance and decrease the interelectrode capacitance of the first stage. Stray capacitance to ground is greatly attenuated by a shield, driven at signal level, that completely surrounds the circuit.

A block diagram of the instrumentation used on cone firings is shown in Figure 8. When the cone passes at the detector position, it interrupts part of the light on one, two or even three detectors depending on its position. The bell-shaped pulses from the detectors are fed to a multi-input analog comparator which instantaneously compares their heights. The decision is stored for a duration of 10 milliseconds. At the same time a series of gates are operated to feed the incoming triggering pulse to the selected -30 Kv pulse generator and cathode. Synchronization of the pulses applied to the anode and the selected cathode is critical in this case due to the smaller spacing (about one inch) between adjacent cathodes. To increase this distance the steel rod cathodes are recessed by about one inch inside the cylindrical nylon insulator seen in Figure 6.

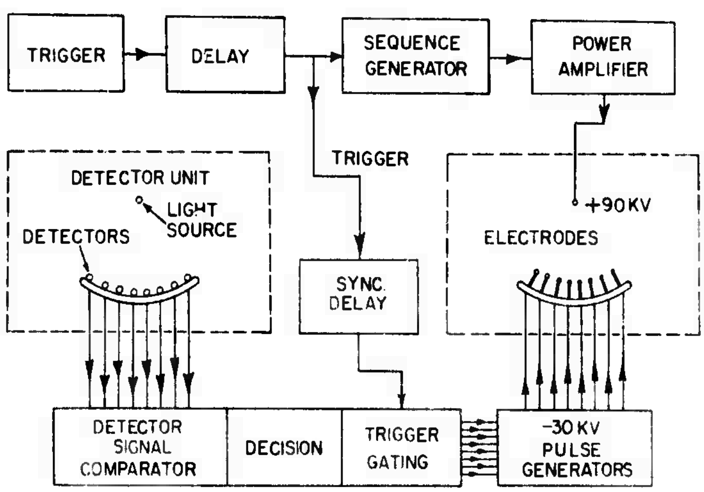


**FIGURE 8 – Diagram of Instrumentotion Used for Cone Wake Meosurements**

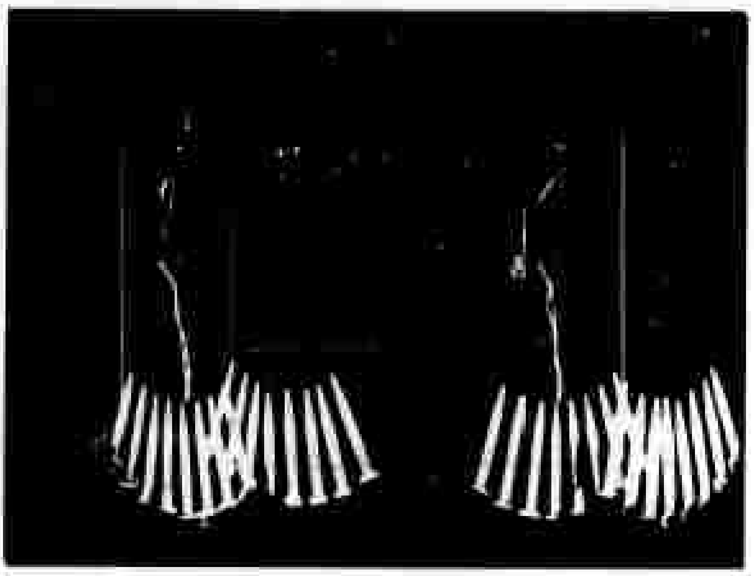

**FIGURE 9 – Stereo Photographs of Two Sequences of Sparks Made in the Wake of a Hypersonic Cone**

All attempts made to produce a second sequence of sparks on a second set of electrodes on the same firing have been unsuccessful because of the small diameter of the flowfield. The stereo photographs of Figure 9 show two sequences of sparks made at 100 and 600 body diameters behind a 10° half angle cone travelling at 15,000 ft/sec at an ambient pressure of 100 torr. Even if the switching of the second sequence to the second array of electrodes has been unsuccessful, the two sequences are however spatially separated. During the interval between the two sequences, the portion of turbulent wake on which the first sequence was made has flown past the spark station and has been replaced by a new portion of wake. The column of gases heated by the sparks in the lower velocity inviscid wake has moved by a small distance. The second sequence has followed this heated channel and the displacement was sufficient to separate the two sequences. This mechanism has proved sufficiently reliable to permit the measurements of double sequences on cone firings.

## 4.0 TREATMENT OF THE DATA

### 4.1 Data Recording and Reduction Techniques

The first few measurements with the sequential spark showed that the sparks did not generally pass through the center of the wake along a straight line. This was especially true on hypersonic wake measurements where on slightly off-axis firings, the sparks could jump sideways from the top electrode, pass through a section of the wake and curve back to reach the bottom electrode. This fact dictated the need for precise stereo recording and analysis of the spark traces if spatially resolved measurements of the wake velocity were to be obtained.

A three-dimensional record of the spark traces is obtained from the precision stereo system illustrated by the top view of the range shown in Figure 10. This system consists of two cameras whose optical axes lie in the horizontal plane and intersect in the center of the range at the spark station. One camera looks downrange at 60 degrees from the flight axis, while the other looks in an uprange direction, also at 60 degrees from the flight axis. This top view of the spark station also shows the four plumb lines spaced by 8.5 inches and the two catenary lines at 12 inch distance which are used as references for the precision stereo system. The catenary lines are also used as references for the flash X-ray photoattitude system of the range (11). The use of the same reference lines for the photoattitude and the spark station stereo systems permits the accurate positioning of the projectile with respect to the spark traces. Shadows of the horizontal and vertical reference lines can be clearly seen in the stereo photographs of Figure 5. The cameras, which use 2.5 inch diameter aerial photo lenses with a focal length of 7.5 inches are located about 3.5 feet from the electrode position giving a magnification of about 0.2. Spectroscopic glass plates are used to assure the dimensional stability required by the precision stereo system.

The data reduction of the stereo photographs is made on the stereo projector assembly shown in the photograph of Figure 11. This assembly reproduces the geometry of the range stereo system and uses the same type of lenses. One of the projectors consisting of a 500 watt incandescent lamp, a light condensing lens, a photographic plate holder and a projection lens can be seen on the top left-hand corner. The stereo system is rotated by 90 degrees with respect to the range system (optical axes in the vertical plane). Alignment of the system is made from the shadows of reference lines on the stereo photographs. The square defined by the four plumb lines shown in Figure 10 can be reproduced to within 1/32 of an inch.

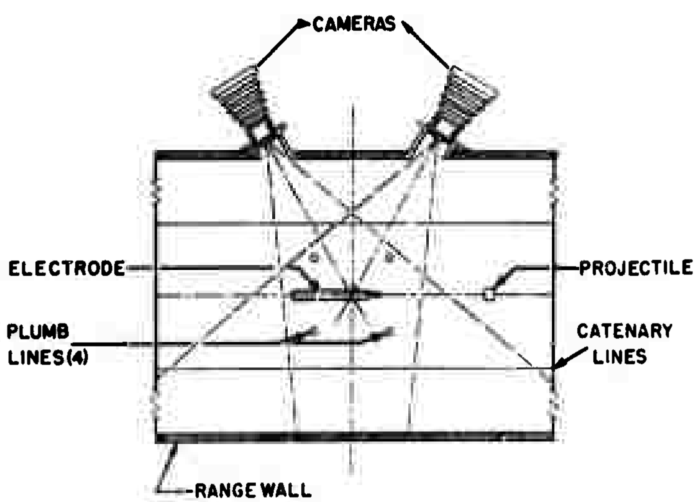


**FIGURE 10 – Top View of the Stereo System Used to Photograph the Spark Sequences**

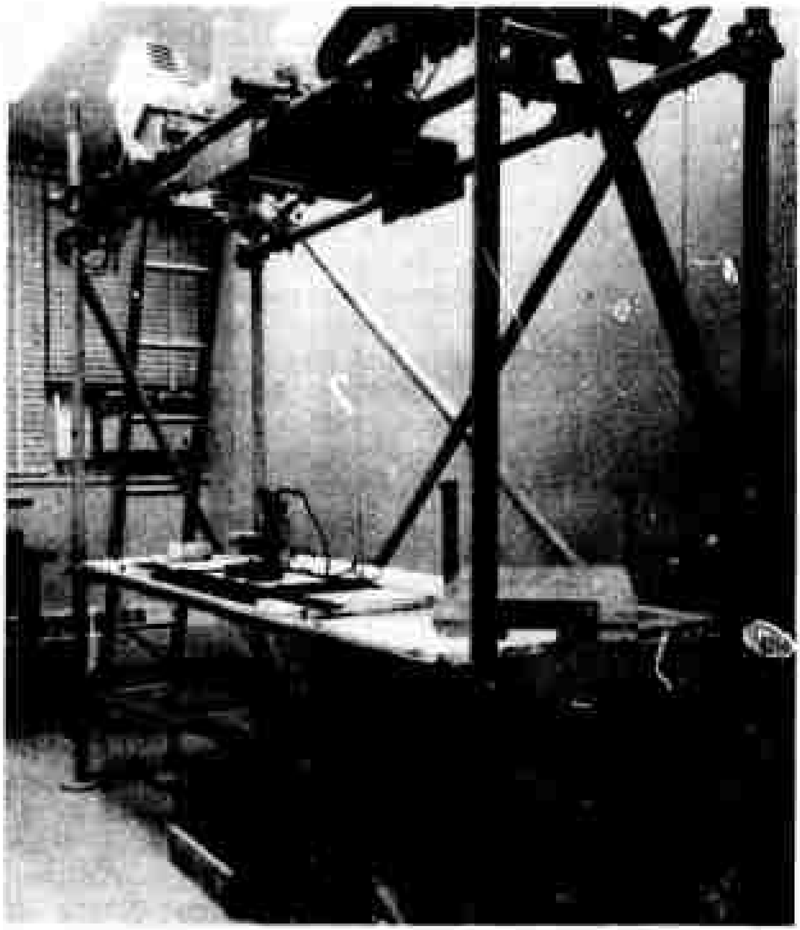

**FIGURE 11 – Photograph of the Projector Assembly**

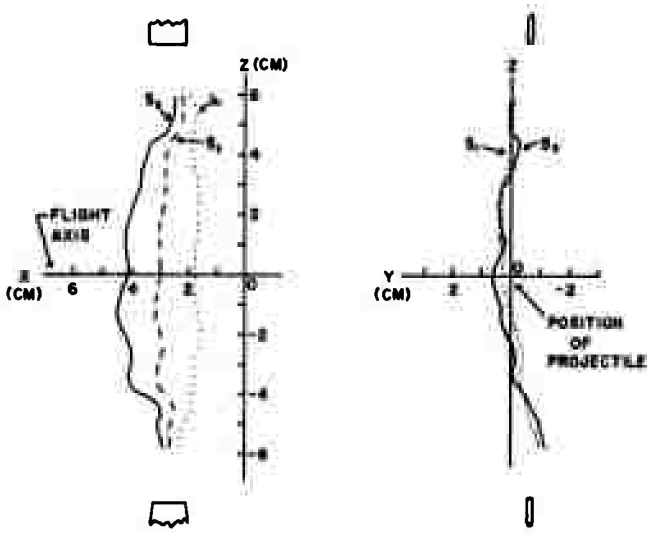


**FIGURE 12 – Projections of the Spark Traces**

## 4.2 Method of Analysis

The spark sequence on the left of Figure 5 is utilized to give an example of the data reduction procedure. After the alignment of the projector assembly is completed the orthogonal coordinates of numerous points of each spark traces are determined by standard photogrammetric techniques. Figure 12 shows projections of spark traces in the xz and yz planes where the x axis is the direction of the flight, the z axis is the vertical direction in the range and the y axis is the horizontal direction. The position of the electrodes in both planes are indicated. The position of the projectile with respect to the spark traces is determined from the flash X-ray photoattitude system with an accuracy better than 0.05 inch. In the present case, coordinates have been read at interval of 0.3 cm along the z-axis. Only the first and third spark traces are shown in the y z plane because of the small separation between the traces.

Before a velocity of the wake can be calculated from these successive positions of the spark, it is necessary to make the assumption that the velocity in the z direction is equal to zero. Once this assumption is made, the velocity components can be computed in both planes of Figure 12 from the horizontal distance between consecutive spark traces and from the time intervals between the sparks. The radial position of the measurements can be calculated from the projection of the sparks in the y z plane.

Graphs of the resulting velocity profiles obtained from consecutive pairs of sparks are given in Figure 13. The notation $V_{12}$ indicates the velocity profile computed from the first and second sparks, and $V_{23}$ from the second and third sparks. The wake velocity is normalized with respect to the projectile velocity $V_\infty$, and the radial distance R is normalized to the sphere diameter. The graph on the left shows the axial wake velocity calculated from the spark traces in the x y plane while the graph on the right gives the lateral velocity calculated from the spark traces in the y z plane. In this latter graph, lateral velocity in the direction of stereo cameras is arbitrarily set positive. No measurement is made at R/D = 0 because the spark traces miss the center of the wake.

## 4.3 Accuracy of the Technique

The accuracy of the velocity measurements made with the sequential technique depends on the following factors: the precision with which the coordinates of the spark traces can be measured on the projector assembly, the precision of the measurement of the time interval between the sparks and the distortion of the spark path produced by the electric field. Because of its inherent precision, the alignment of the projector assembly has a negligible contribution to the total error.

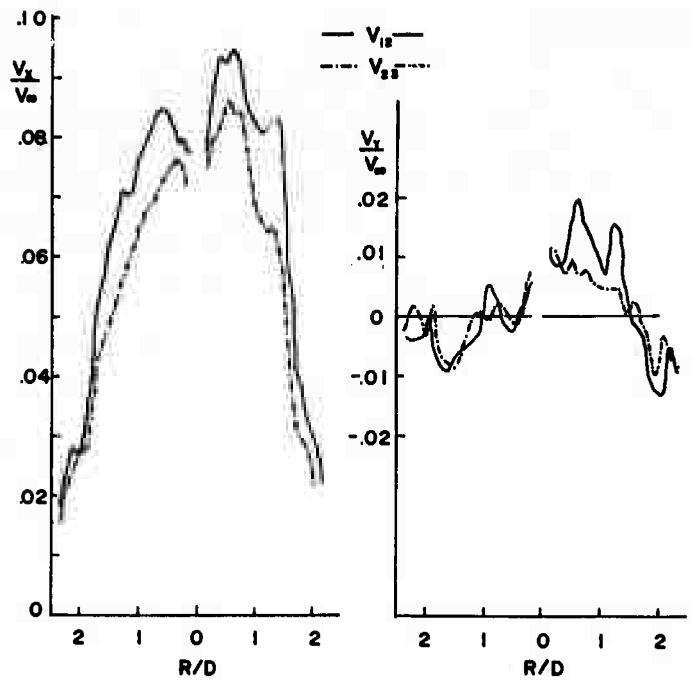


**FIGURE 13 – Velocity Profiles Obtoined from the Projections of Figure 12**

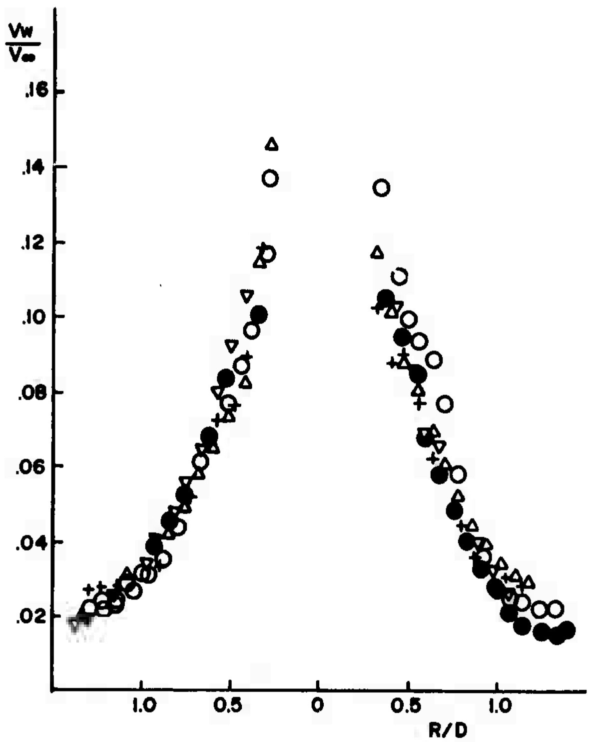


**FIGURE 14 – Sample of Five Velocity Profiles Measured in the Inviscid Woke of Supersonic Spheres**

The coordinates of the spark traces are obtained by means of the tracing table seen on the projector table in Figure 11. Coincidence of the spark traces from the two projectors is made with a floating luminous mark on the white circular platen. The coordinates x and z are obtained by projecting the coincidence point on a graph sheet disposed on the projector table by means of a pointer. The coordinate y is read from a dial that indicates the height of the platen. The accuracy depends on the ability of the operator to align the center of the spark traces with the floating mark and to read the coordinates on the graph sheet. The accuracy of the measurements is limited by the resolution of the human eye. Typically, a precision of about 0.015 inch is achieved on each orthogonal coordinate.

The intervals between the sparks are measured to an accuracy of about two percent. The intervals are adjusted on a calibrated oscilloscope prior to the firings, and a photograph of the pulse sequence is taken during the firing as a control. The nominal value of the spark intervals is used in the calculation of the velocity.

As an example of the accuracy that can be achieved with the sequential spark technique, Figure 14 shows five profiles of the inviscid wake velocity measured on one inch diameter spheres under almost indentical conditions of velocity (4,000 ft/sec) and of ambient pressure (100 torr). These measurements were made at an axial distance of about 15 diameters behind the sphere. Each profile, represented by a different symbol, is the average of eight estimates obtained from the nine sparks of the sequence. The standard deviation of the data with respect to the mean profile is 0.0035, or 3.5 percent if normalized to a velocity ratio $V_W/V_\infty$ of 0.1. Because of the absence of turbulence in the inviscid region of the wake, the standard deviation can be expected to represent reasonably well the accuracy of the measurement.

The third factor affecting the accuracy of the spark technique is the distortion produced on the spark traces by the electric field generated by the voltage pulses applied to the electrodes. When an electric field is applied in the presence of charges, a drift velocity proportional to the electric field is induced on these charges. The constant of proportionality is the mobility coefficient, which itself is directly proportional to the temperature and inversely proportional to the pressure. The situation occurring in the spark experiment is described in Figure 15. From the voltage pulses applied to the electrodes, it can be seen that the electric field takes a different value before and after the formation of the ionized path. The first two +90 Kv pulses applied on the anodes produce only a glow across the gap and the electric field, which has a value of 8 Kv/cm (120 Kv across a 15 cm gap), is applied for 0.8 microsecond. On the third pulse, the voltage rises to about 60 Kv on the anode and then breakdown occurs. The electric field has a value of about 4 Kv/cm, and it is applied for about 0.2 microsecond. On each successive spark after the third one, the same situation observed on the third pulse prevails. During the first part of the sequence, the concentration of charged particles is low and the effect of the 8 Kv/cm field can be neglected. With the formation of the spark channel, the concentration of charged particles is high and the effect of the electric field cannot be neglected.

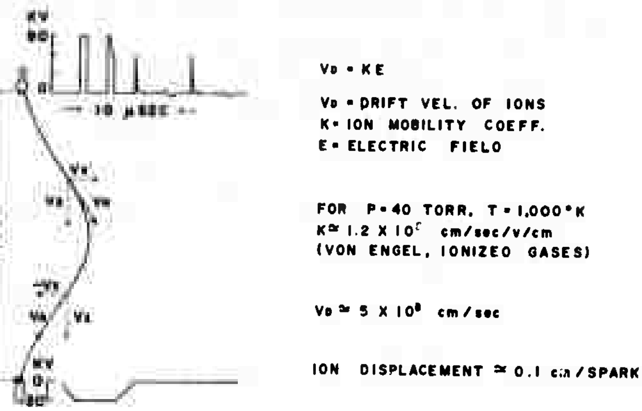


**FIGURE 15 – Electric Field Effect**

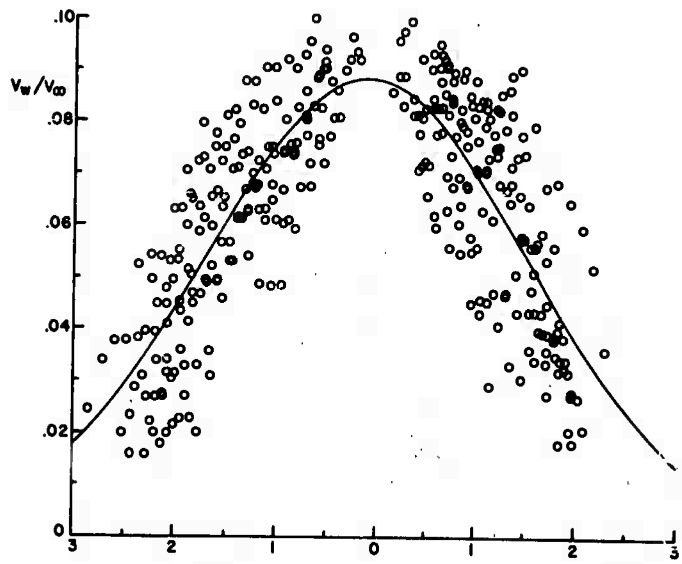


**FIGURE 16 – Typical Sample of Twelve Velocity Profiles Measured at 300 Diameters Behind Hypersonic Spheres**

A theoretical estimate of this effect has been made for a pressure of 40 torr and a typical temperature of 1000°K; a coefficient of ion mobility of 1.2 x $10^2$ cm/sec/V/cm has been used (13). For an electric field of 4 Kv/cm, the drift velocity of ions is 5 x $10^5$ cm/sec and for a duration of 0.2 microsecond, a displacement of the ions of about 0.1 cm is obtained for each spark.

Because the spark path is much more ionized that the ambient wake, the electric field lines are perpendicular to the spark path and then the drift velocity of the ions is parallel to the path. On a curved path, such as the one shown in Figure 15, the drift velocity can be resolved in two components, one in the axial direction and the other in the downward direction. In the upper portion of the wake, the axial component tends to increase the wake velocity whereas in the lower one it tends to decrease it. The result of this effect is a slight asymmetric of the mean profile obtained from series of measurements under identical conditions. The effect which is appreciable on profiles measured at 40 torr is almost negligible on measurements made at 100 torr behind hypersonic spheres.

## 5.0 TYPICAL RESULTS AND LIMITATIONS OF THE TECHNIQUE

### 5.1 Typical Results

The sequential spark technique has been used over the past few years to investigate wake velocity distributions of projectiles in free flight under a large variety of experimental conditions. Figure 16 shows a typical sample of 12 radial profiles of velocity collected at 300 diameters behind one inch diameter spheres travelling at 14,500 ft/sec in an ambient pressure of 40 torr. Again, the wake velocity $V_W$ is normalized to the sphere velocity $V_\infty$ and the radial distance R to the sphere diameter D. Figure 16 also shows the slightly asymmetric gaussian curve which has been fitted on the data by the least mean squares method. The asymmetry of the profile is due to the electric field effect which has been described earlier. To minimize this effect, only the axial displacement between the first two sparks of each sequence has been used to estimate the velocity. The standard deviation of the data points with respect to the asymmetric curve is 0.0127, or 14.7 percent, when normalized to the wake axis velocity ratio. This value of standard deviation is reasonable if one takes account of the fact that it sums up contributions from the wake turbulence intensity, the goodness of the fit and the experimental error. The data collected with the sequential spark technique show good agreement with those obtained in ballistic ranges by Heckman et al. with the electrostatic probe technique (14) and by Fox and Rungaldier with the anemometer technique (15).

### 5.2 Limitations of the Technique

Experimentation has revealed a number of factors that limit the application of the sequential spark technique. These factors are related to the specifications of the equipment and to the conditions of the flow field to be measured.

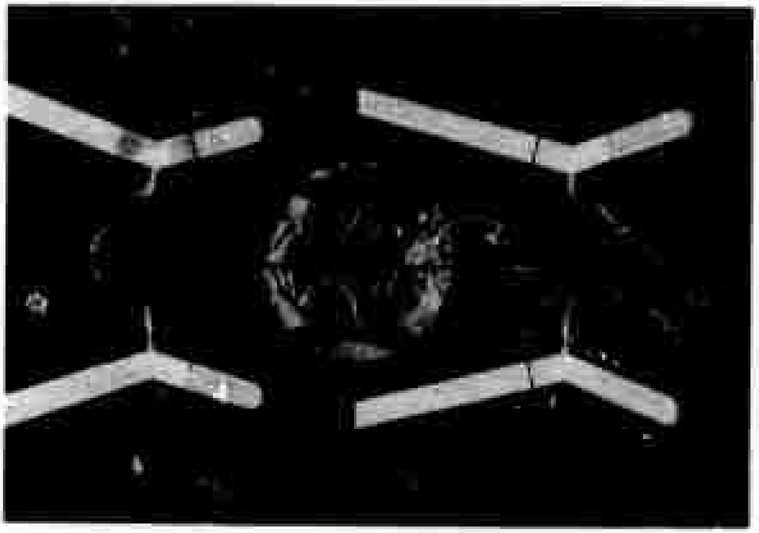

FIGURE 17 – Sequence of Sparks Made at 140 Diameters Behind a Hypersonic Sphere

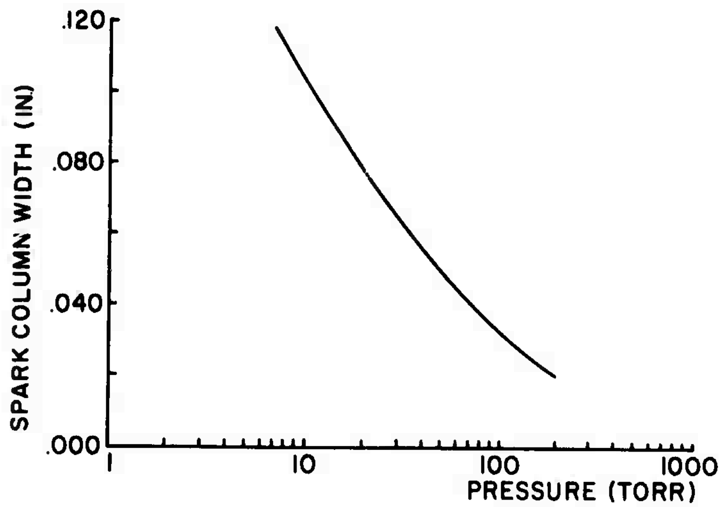


FIGURE 18 -- Spark Column Width Versus Pressure

The 90 Kv pulses available for the discharges impose some limitations to the combination of the electrode gap and operating pressure that can be used if rapid breakdown of the gap is to be achieved. With a six inch electrode gap, the range of operating pressures is from 10 to 200 torr. At 200 torr, a train of four pulses at intervals of 3 microseconds is necessary to initiate the discharge. Below 10 torr, a glow discharge is obtained and a well defined spark cannot be formed. The six inch electrode gap is barely adequate to study the wake of one inch diameter spheres. At large axial distance behind the model (X/D > 1000), the electrodes are immersed in the viscous wake and only the center of profile is measured.

The flowfield itself imposes some limitations to the application of the spark technique. At distances up to approximately 150 body diameters on hypersonic spheres at 40 torr, it is not possible to form a well-defined spark in the center of the viscous wake because of the high ionization level of the gas. The sequence of sparks shown in Figure 17, made at approximately 140 diameters behind a one inch sphere travelling at 14,250 ft/sec in an ambient pressure of 76 torr, illustrates this problem. The spark traces which are well formed on the edge of the viscous wake become completely diffused in the central core. Diffusion of the spark in the center is due to the high conductivity of the gas. At a pressure of 100 torr, the same problem is observed at axial distances up to 300 body diameters.

The range of velocities that can be measured with the sequential spark technique is determined at high velocity by the maximum repetition rate of the equipment, and at low velocity by the width of the spark column and by the maximum persistence of the ionized path.

On non-ionized flowfields, a maximum velocity of 10,000 ft/sec could be measured with spark intervals of 3 microseconds. The pulse duration of 0.8 microsecond would however affect the accuracy of the measurement. Measurement of such velocities is not possible on hypersonic wakes because of the ionization of the gases. The maximum velocity that has been measured in that case was about 3,000 ft/sec.

The resolution of the technique on low velocity flowfield is a function of the spark column width and of the persistence of the ionized path. Figure 18 shows a curve of the spark column width versus the ambient pressure obtained from measurements on the stereo photographs of the sparks. Such a curve depends strongly on the optical system used to photograph the sparks. The cameras described earlier are operated at f/11 for the measurements. The spark width varies from 0.120 inch at 10 torr to about 0.020 inch at 200 torr. At 100 torr, the spark column width is about 0.030 inch. If one assumes that a displacement of twice the value of the spark width can be resolved on the photographic plates then a minimum velocity of 25 ft/sec can be measured using a spark interval of 200 microseconds, the maximum value permitted by the persistence of the ionized path. At low pressure the resolution is considerably reduced because of the increased spark width.

## 6.0 CONCLUSION

A description has been given of the sequential spark technique and of its application to ballistic ranges for the measurement of velocity in the wake of projectiles in free flight. This unique experimental technique has been utilized extensively over the past few years to determine wake distributions behind classical models of various shapes and sizes under a large range of ambient conditions. It has produced a wealth of novel data which have contributed to a better understanding of the wake structure.

The sequential spark technique can also be adapted to the study of flowfields in a large variety of situations. It is especially well suited for application to wind tunnels where it could permit visualization of complex flowfields through the use of a large number of sparks.

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